

SCIENCE FOR GLASS PRODUCTION

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THEORETICAL HEAT CONSUMPTION IN GLASSMAKING

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A method for calculating the theoretical heat consumption in glassmaking has been developed for the zonal method of calculating exterior heat transfer. Computational results are presented for heat consumption in a 280–420 tons/day container-glass furnace.

Key words: glass furnace, glassmaking, computational method, heat consumption.

In solving the exterior problem of heat transfer in gas-electric glass furnaces the source term ($-Q_{gf}$) in the nonlinear equations of heat transfer and heat balance for the surface zones of the molten glass with boundary conditions of the second kind is calculated from the expression [1]

$$Q_{gf} = Q_{1.1} + Q_{1.2} + Q_{m.mt} - Q_e, \quad (1)$$

where $Q_{1.1}$ and $Q_{1.2}$ are, respectively, the heat consumption in glass formation and heating of the molten glass, kW; $Q_{m.mt}$ represents the heat losses through the melting tank masonry, kW; and, Q_e is the additional electric heating (AEH), kW.

To calculate heat transfer by the resolvent zonal method [2] the equation determining $Q_{1.1}$ [5] is put into the form

$$Q_{1.1} = P_{fc} G_b (q_{\Sigma} + q_{1.i}), \quad (2)$$

where P_{fc} is the furnace capacity, kg/sec; G_b is the batch consumption per 1 kg molten glass, kg/kg; q_{Σ} is the total heat of the glass-forming reactions per 1 kg batch, kJ/kg.

Here

$$q_{1.i} = q_{1.1} + q_{1.2} + q_{1.3} + q_{1.4},$$

where $q_{1.1}$, $q_{1.2}$, $q_{1.3}$ and $q_{1.4}$ are, respectively, the heat consumption in evaporation of moisture and heating the primary melt and products of degasification and glass melting, kJ/kg.

The batch consumption per 1 kg molten glass is

$$G_b = \frac{1}{G_{mg}},$$

where G_{mg} is the yield of molten glass per 1 kg batch, kg/kg.

In turn

$$G_{mg} = 1.0 - 0.01 G_{p.d} + G'_c$$

and

$$G'_c = \frac{G''_c}{100 - G''_c},$$

where $G_{p.d}$ is the total yield of the products of degasification per 1 kg batch, kg; G'_c is the cullet consumption per 1 kg batch, kg/kg; G''_c is the cullet fraction in the total mass of batch and cullet, %.

The total heat of the glass formation reactions per 1 kg batch is determined from the relation

$$q_{\Sigma} = 0.01 \sum_{i=1}^n G_i q_i,$$

where G_i is the mass of the i th oxide, kg; q_i is the specific heat consumption in the reaction producing the i th oxide, kJ/kg; and, n is the number of oxides.

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The mass of the i th oxide per 100 kg batch is found from the expression

$$G_i = \sum_{i=1}^k G_{b,rm} K_0 (10 - H_2O),$$

where $G_{b,c}$ is the content of the i th material in the raw materials used in the batch, %; K_0 is the content of the main substance or corresponding oxide of the i th component, fractional content; H_2O represents the moisture content of the batch, fractional content; and, k is the number of batch components containing the i th oxide.

The heat consumption in the evaporation of moisture is

$$q_{1,1} = K H_2O,$$

where $K = 2514$ is the heat consumption in the evaporation of 1 kg moisture, kJ/kg.

The heat consumption in heating primary melt is

$$q_{1,2} = G_{mg} c_{mg} (t_{mg} - t_b),$$

where c_{mg} is the specific heat capacity of the primary melt at t_{mg} , kJ/(kg · K); t_{mg} is the maximum heating temperature of the molten glass in the melting tank, °C; and, t_b is the batch temperature at the time of loading into the furnace, °C. We shall take $t_{mg} = 1500^\circ\text{C}$ and $t_b = 40^\circ\text{C}$.

The temperature dependence of the specific heat of the primary melt is given by the equation

$$c_{mg} = 4.187 \times (0.1605 + 1.1 \times 10^{-4} t_{mg}).$$

The heat consumption in heating the products of degasification is given by the relation

$$q_{1,3} = 0.01 V_{p,d} c_{p,d} t_{p,d},$$

where $V_{p,d}$, $c_{p,d}$, and $t_{p,d}$ are, respectively, the volume (per 100 kg batch), m^3 , the average specific heat, kJ/($\text{m}^3 \cdot \text{K}$), and degasification temperature, °C. We shall take $t_{p,d} = 1500^\circ\text{C}$.

The volume of the products of degasification is calculated from the equation

$$V_{p,d} = \sum \frac{G_i}{\rho_i},$$

where G_i is the total yield of the i th component of degasification kg; ρ_i is the density of the i th component of degasification, kg/m^3 .

The heat consumption in glass melting is

$$q_{1,4} = 347.52 \times (10 - 0.01 G_{p,d}).$$

In the heat balance for the melting part of the furnace the quantity $Q_{1,2}$ represents the heat carried away by the working flow of the molten glass [4]. In the zonal calculation of heat transfer $Q_{1,2}$ is the heat consumption in heating cullet to the

maximum temperature of the molten glass in the melting tank

$$Q_{1,2} = P_{fc} G_c c_c (t_{mg} - t_c), \quad (3)$$

where G_c is the cullet consumption per 1 kg molten glass, kg/kg; c_c is the specific heat of the cullet, kJ/(kg · K); and, t_c is the temperature of the cullet at the time of loading into the furnace, °C. We take $t_c = 40^\circ\text{C}$.

The specific heat of the cullet is calculated from the relation

$$c_c = 4.187 \times (0.1794 + 0.632 \times 10^{-4} t_{mg}).$$

The cullet consumption per 1 kg molten glass is

$$G_c = \frac{G'_c}{G_{mg}},$$

or

$$G_c = G_b G'_c. \quad (4)$$

Substituting the expression (4) into Eq. (3) we obtain

$$Q_{1,2} = P_{fc} G_b G'_c c_c (t_{mg} - t_c). \quad (5)$$

Summing the left- and right-hand sides of Eqs. (2), (5) and rearranging we obtain an expression for calculating the theoretical heat consumption in glassmaking Q_t , kW,

$$Q_{\text{theor}} = P_{p,d} G_b [(q_\Sigma + q_{1,1} + q_{1,2} + q_{1,3} + q_{1,4}) + G'_c c_c (t_{mg} - t_c)]. \quad (6)$$

We shall now put Eq. (6) into a form suitable for the zonal method of calculating the external heat transfer:

$$Q_{\text{theor}} = P_{p,d} (q_{mg} + q_h), \quad (7)$$

where q_{mg} is the specific consumption of heat on glass formation, kJ/kg, and q_h is the specific heat consumption in heating the primary melt and cullet, kJ/kg.

In turn,

$$Q_{mg} = G_b (q_\Sigma + q_{1,1} + q_{1,3} + q_{1,4}); \quad (8)$$

$$q_h = G_b [q_{1,2} + G'_c c_c (t_{mg} - t_c)]. \quad (9)$$

Separating the consumption in glass formation (8) and heating (9) in the total theoretical heat consumption in glassmaking (7) makes it possible to differentiate their distribution along the melting tank [3].

To illustrate the method of determining Q_{theor} we shall examine the computational results obtained for the heat consumption in glassmaking for a 280–420 tons/day container-glass furnace (melting tank area 115.77 m^2). The chemical composition of the glass is as follows (wt.%): 71.9SiO₂, 2.0Al₂O₃, 0.2Fe₂O₃; 9.6CaO; 2.2MgO; 13.1Na₂O;

TABLE 1. Batch Recipe for 100 kg Molten Glass

Raw material	Content by weight	
	Parts	%
Quartz sand, GOST 22551–71, PB-150 brand	65.80	55.995
Nepheline – feldspar material, TU 5726-036-001193861, PShS-0.2-21 brand	8.55	7.276
Ground dolomite, GOST 23672–79, DM-20-0.1 brand	10.77	9.165
Chalk, technical, TU 113-08-667–98, A brand, grade 1	10.37	8.825
Soda ash, technical, GOST 5100–85, A brand, highest grade	20.09	17.096
Sodium sulfate, technical, GOST 6318–77, highest grade	1.57	1.336
Chromium colorant, TU 2362-001-70470322–2006, A brand	0.25	0.213
Charcoal, granular, TU 12.36.210–91	0.11	0.094
Total:	117.51	100

0.55K₂O; 0.25Cr₂O₃; and, 0.2SO₃. The batch recipe is presented in Table 1.

The content of recycled cullet in the total batch and cullet mass is 30%. The moisture content of the batch is 4%.

Computational Results for the Intermediate Data for Eq. (6) as well as q_{mg} and q_h

$G_{p,d}$, kg/100 kg batch	19.79
$V_{p,d}$, kg/100 kg batch	12.68
G'_c , kg/kg batch	0.429
G_{mg} , kg/kg batch	1.231
G_b , kg/kg glass mass	0.812
G_c , kg/kg molten glass	0.348
c_{mg} , kJ/(kg · K)	1.3229
c_c , kJ/(kg · K)	1.1481
$c_{p,d}$, kJ/(m ³ · K)	2.1518
$q_{1,1}$, kJ/kg	100.56
$q_{1,2}$, kJ/kg	2377.60
$q_{1,3}$, kJ/kg	409.27
$q_{1,4}$, kJ/kg	278.74
q_Σ , kJ/kg	355.00
q_{mg} , kJ/kg	928.58
q_h , kJ/kg	2514.52

The computational results for the theoretical heat consumption in glassmaking (Table 2) in combination with the coefficients of heat transfer through the furnace masonry [5] make it possible to complete the initial database for determining the source term ($-Q_{mg}$).

We now revisit the data in Table 2. As the glass melting output increases, the theoretical heat consumption in

TABLE 2. Computational Results for the Theoretical Heat Consumption in Glassmaking and Furnace Thermal Power

Furnace capacity, tons/day	Specific glass melting output, tons/(m ² · day)	Q_{theor} , kW	$Q_{p,d}$, kW	$Q_{p,d} - Q_{theor}$, kW
280	2.42	11158.2	15006.9	3848.7
300	2.59	11955.2	15590.3	3635.1
320	2.76	12752.2	16049.9	3297.7
340	2.94	13549.2	16607.4	3058.1
360	3.11	14346.2	17156.2	2810.0
380	3.28	15143.3	17703.8	2560.5
400	3.46	15940.3	18257.3	2317.0
420	3.63	16737.3	18824.0	2086.8

glassmaking increases as does the thermal power of the furnace, given by $Q_{p,d} = BQ_{low}^w + Q_e$, kW (B is the gas consumption in the furnace, m³/sec; Q_{low}^w is the lower working heat-generating capacity of the gas, kJ/m³). In view of the known limitation on the temperature of the dinas roof of the furnace (1580 – 1600 °C) the entire increment to the thermal power cannot be realized because of flame heating. It is distributed between the heat of combustion of the fuel (BQ_{low}^w) and the power of the electric-heating of the melt in the melting tank (Q_e). Determining the efficient value of AEH for different values of the specific glass melting output is a topical problem of mathematical modeling of glass furnaces.

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